How do whiskers and hillocks grow in Pb-free Sn coatings?

Fundamental mechanisms controlling stress evolution and whisker growth

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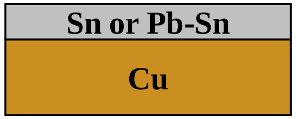
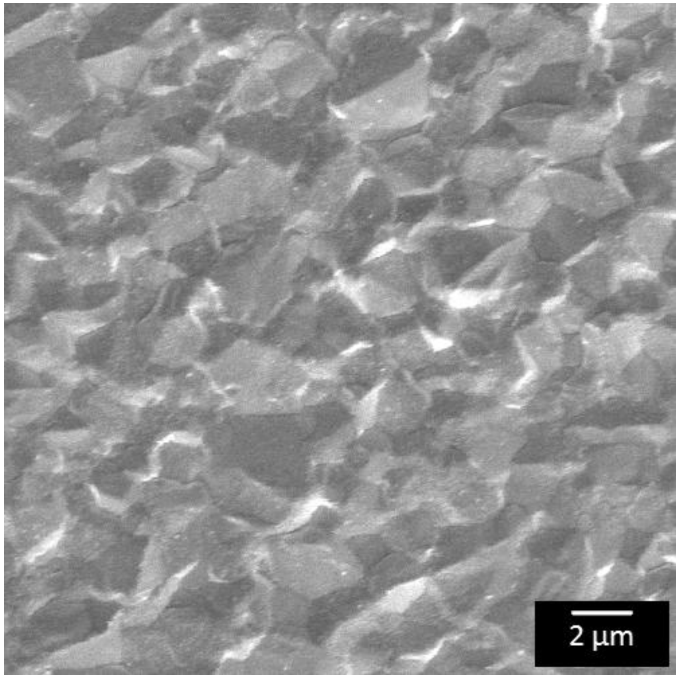
SMTA 2010 Orlando, Fl

- Sn (Pb-Sn alloys) coatings on Cu used commonly by electronics industry
    - Solderability/oxidation resistance



- Push towards Pb-free manufacturing
    - RoHS
- Problem: Pure Sn forms whiskers on Cu
    - Failures in satellites, pacemakers, missiles
    - http://nepp.nasa.gov/whisker
- Driving force believed to be stress from IMC
    - But details not understood



Real-time SEM measurements (4 days)

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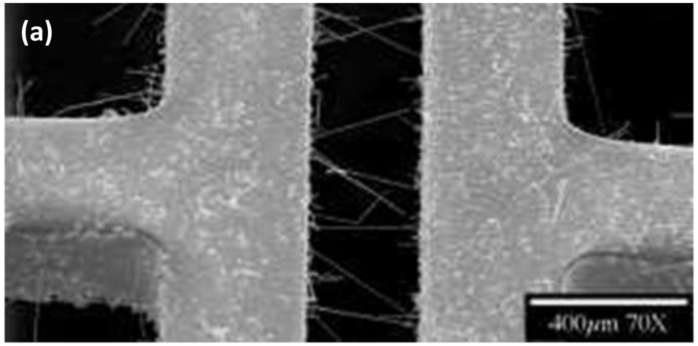
Examples of whisker failures

NASA website: http://nepp.nasa.gov/whisker



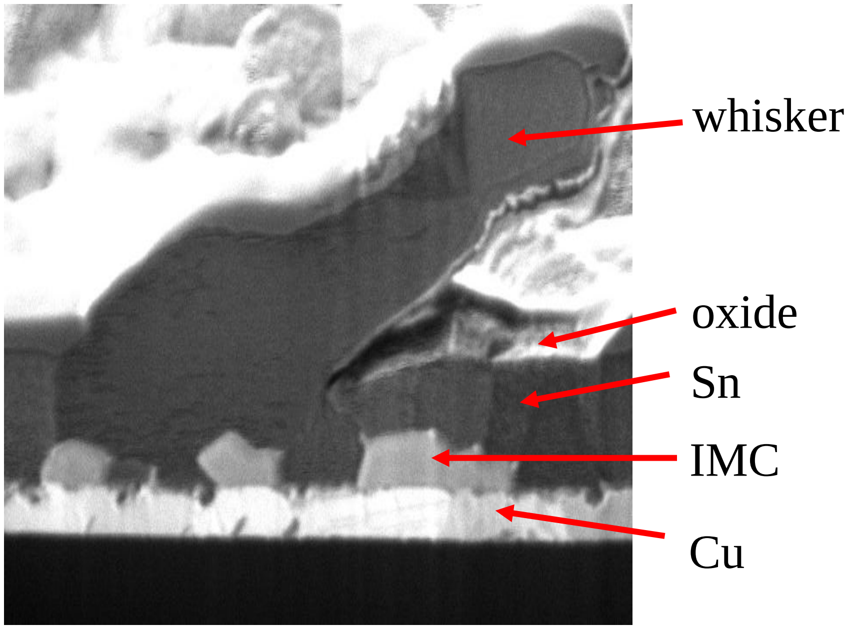
MATTE tin-plated copper lead frame after 3 years of ambient storage

Terminal of a Sn plated relay

Card guide in space shuttle flight box

Relay destroyed by suspected tin whisker-induced metal vapor arc

Difficulty: Multiple materials processes control whisker formation



- Complex multilayer structure with multiple phases

- Sn, Cu, IMC, oxide

- Many kinetic processes to consider:

- microstructural evolution
- (inter)diffusion of Sn, Cu
- intermetallic growth
- stress generation in Sn
- whisker nucleation and growth

- Lots of prior and ongoing work

- many systems/processing methods

Approach: Use systematic measurements to identify mechanisms/develop models

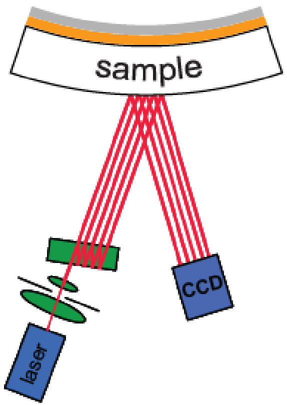
Understand: How does stress relate to IMC growth?

How does stress lead to whisker formation?

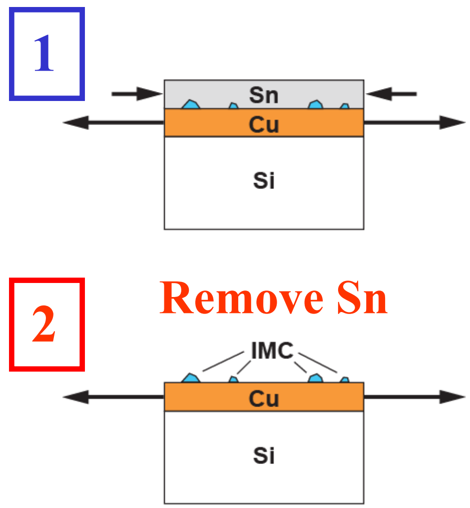
How do whiskers grow?

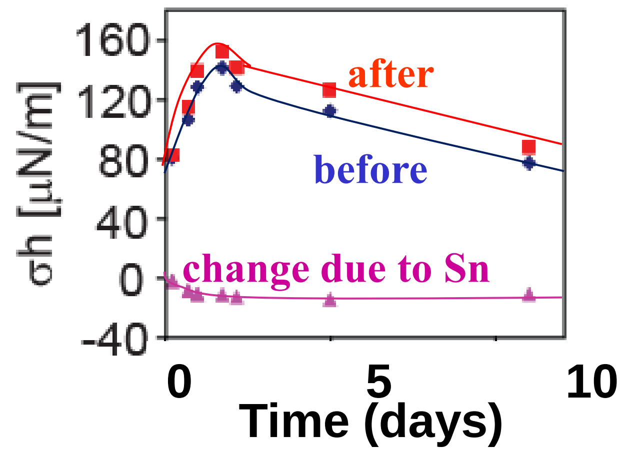
Quantify kinetics of stress/IMC/whiskers in real-time

1) *Stress evolution*



Wafer curvature measures *total* force exerted by film.





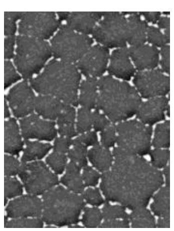
Remove Sn layer – change in curvature gives stress in Sn

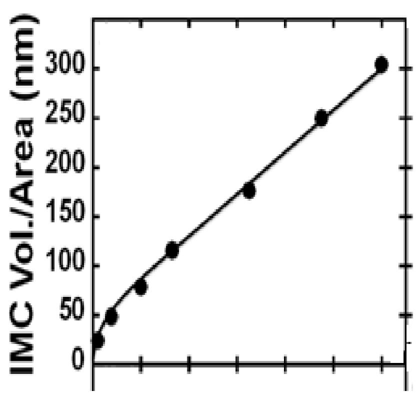
2) *IMC volume*

Selectively etch Sn

Find IMC volume from mass change

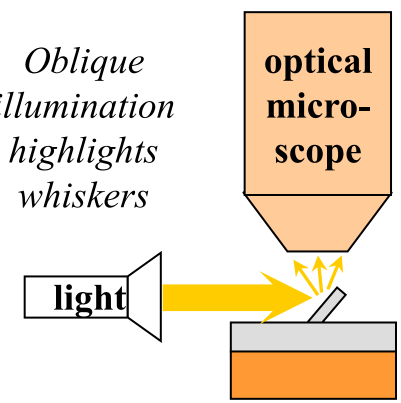
Also IMC morphology

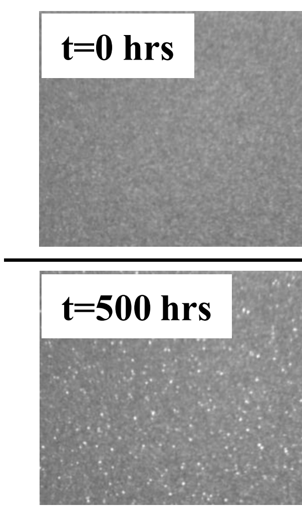




3) *Whisker density*

Oblique illumination highlights whiskers





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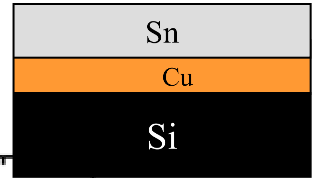
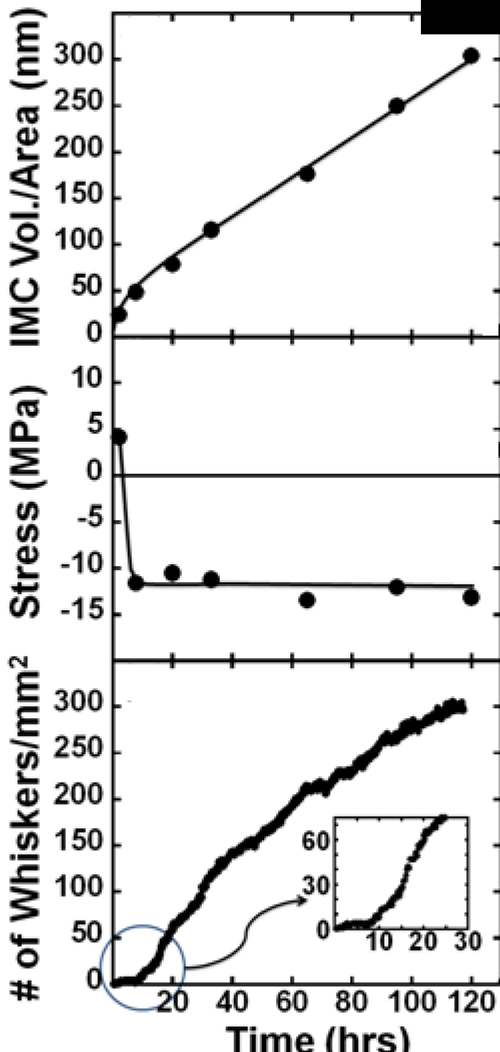
Correlate stress/whiskering with IMC growth

(Chason APL 2008)

Pure Sn on Cu



Samples: Electrodeposited
1.2 micron Sn/0.6 micron Cu



<u>Pure Sn overlayers</u>

- IMC grows continuously (rate slows with time)

- Stress saturates soon after formation of IMC (~12 MPa)

→ Onset of plastic deformation

- Whiskers start to grow after stress saturates (seen in SEM too)

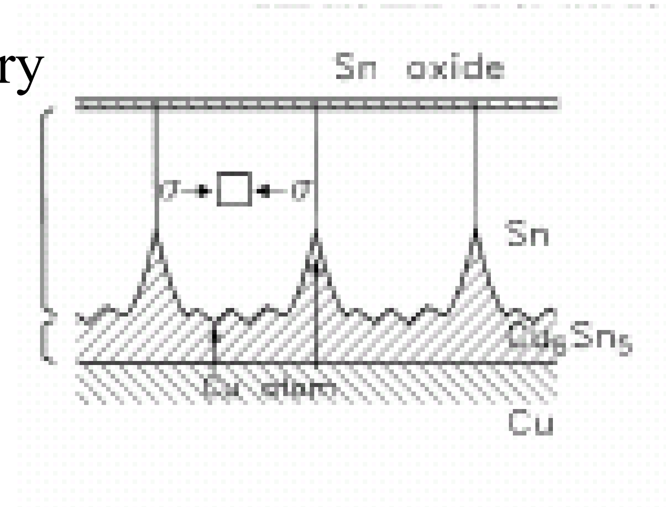
- Have also studied effects of grain size, layer thickness, Pb alloying, annealing (next talk)

What are the mechanisms controlling stress?

“Standard picture”: IMC grows into grain boundary
Creates stress in Sn layer (Lee and Lee,1998)

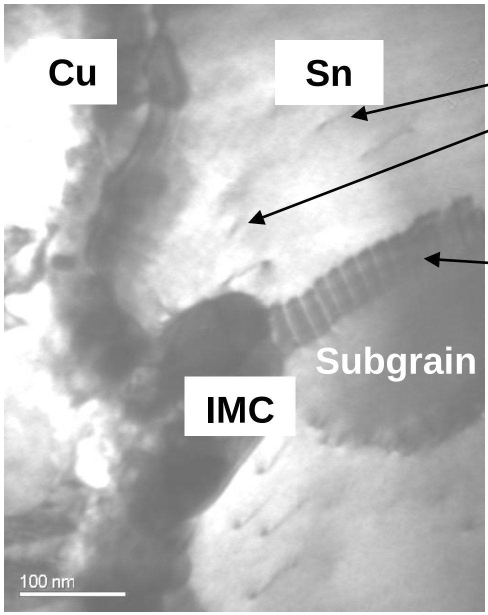
→ *Must be more than elastic effects*

- *Stress exceeds yield stress*
- ***Need to consider plastic deformation***



Stress relaxation by dislocation formation (X-TEM)

(Kumar, JMR 2008)



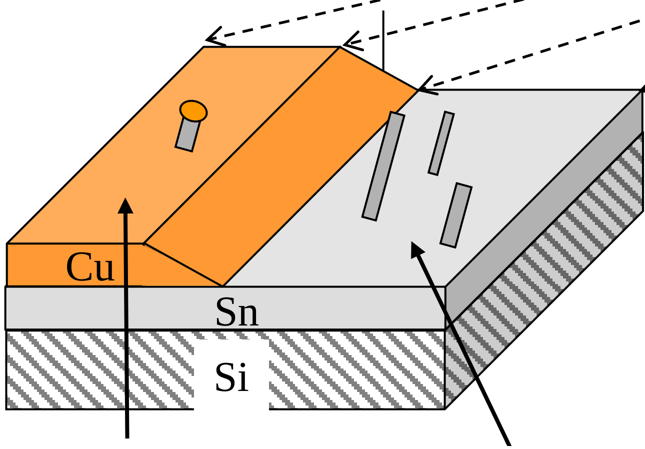
Extensive dislocation emission around IMC particles
- *transmits strain into Sn layer*

Dislocations form into subgrain boundaries (highly mobile)

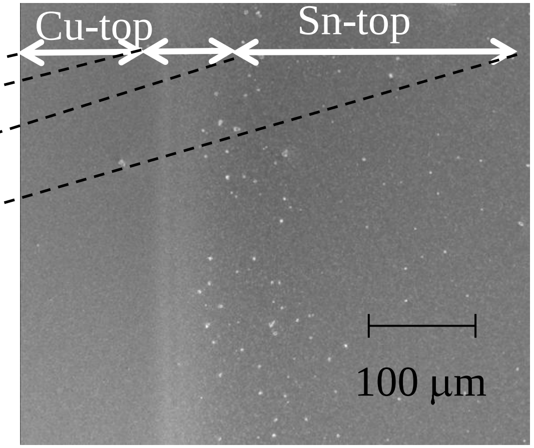
Stress relaxation by grain boundary diffusion: "ledge sample"

(Reinbold, JMR 2009)

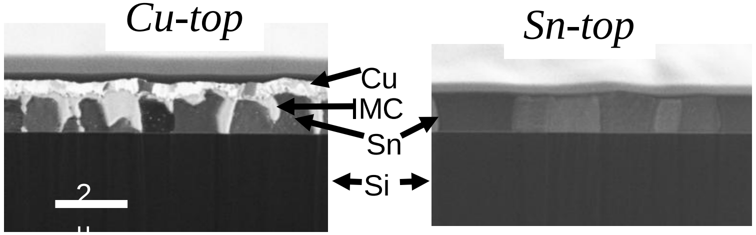
Schematic of ledge sample

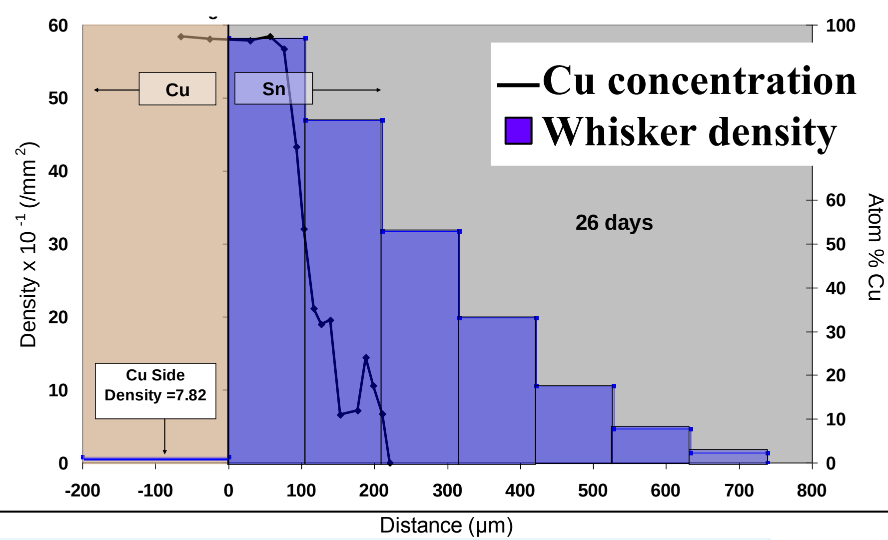


SEM around ledge



- "Ledge": Deposit Cu over **half** of Sn layer
- Monitor whisker density with SEM
- Measure Cu evolution with EDS
- Whiskers form farther out than IMC





FIB images of ledge sample

- *No IMC 700 microns from ledge*
- *But whiskers are seen*

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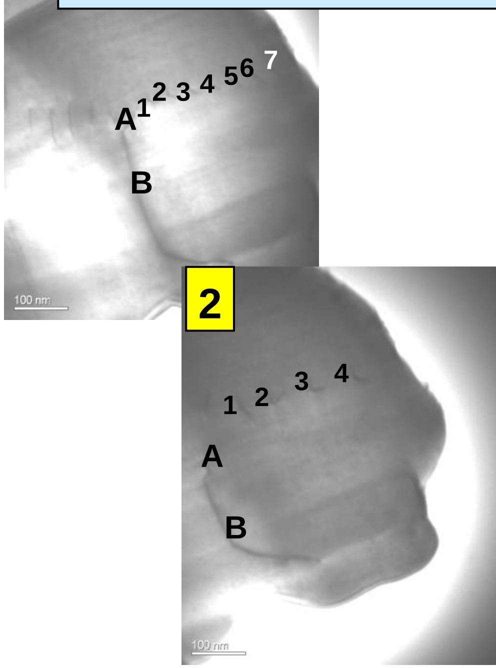
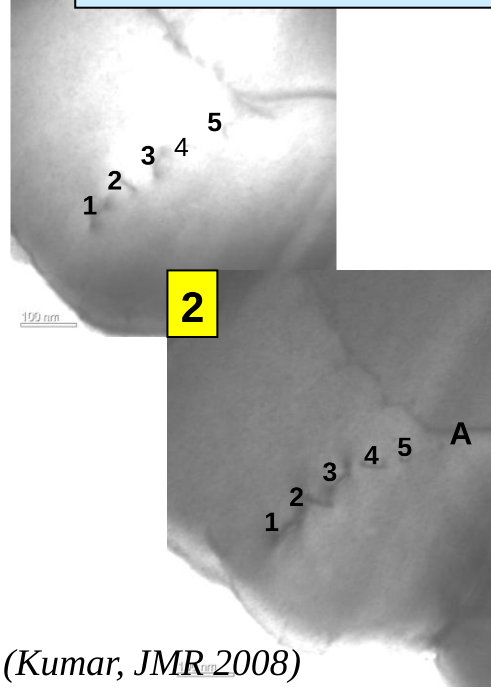
Surface oxide prevents stress relaxation at surface

TEM shows dislocation pile-up at oxide

1 No oxide : dislocations eliminated to relax tin

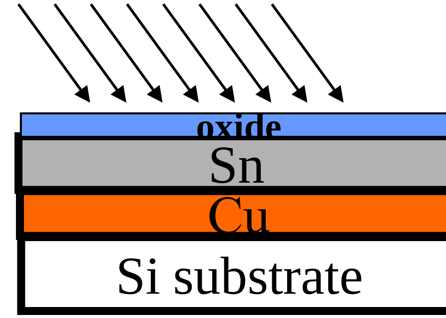


1 w/ Oxide : dislocations pile up/stall at surface



(Kumar, JMR 2008)

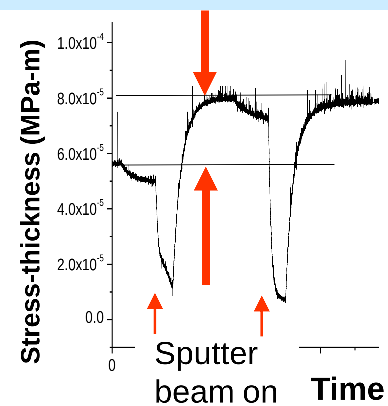
Stress relaxes when oxide removed *(Chason, APL 2008)*



Remove oxide by:

- Sputtering surface in vacuum
- Etching surface in solution

Curvature shows irreversible change due to stress relaxation in Sn



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Put these mechanisms into model using finite element analysis (FEA)

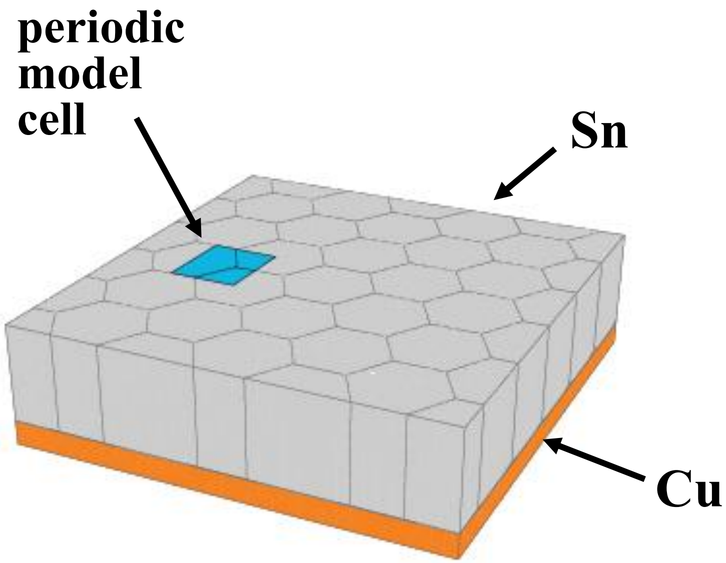
(informed by experiments)

<u>Features of model</u>:

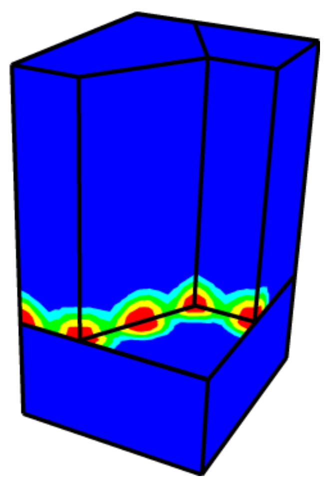
- Polycrystalline Sn film
- Columnar microstructure in Sn
- Cu substrate (homogeneous)
- IMC expansion at Sn/Cu interface (matched to measured V_{IMC} vs. time)

<u>Mechanical behavior</u>:

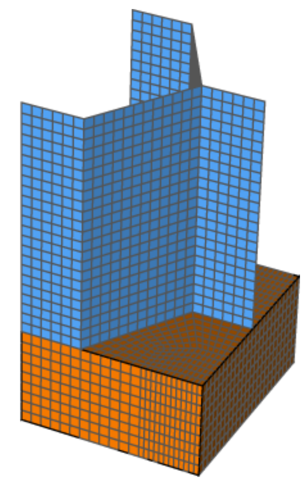
- Elastic deformation (isotropic)
- Plastic deformation (isotropic)
- Stress-driven, grain-boundary diffusion
- No surface diffusion (effect of surface oxide)



IMC expansion

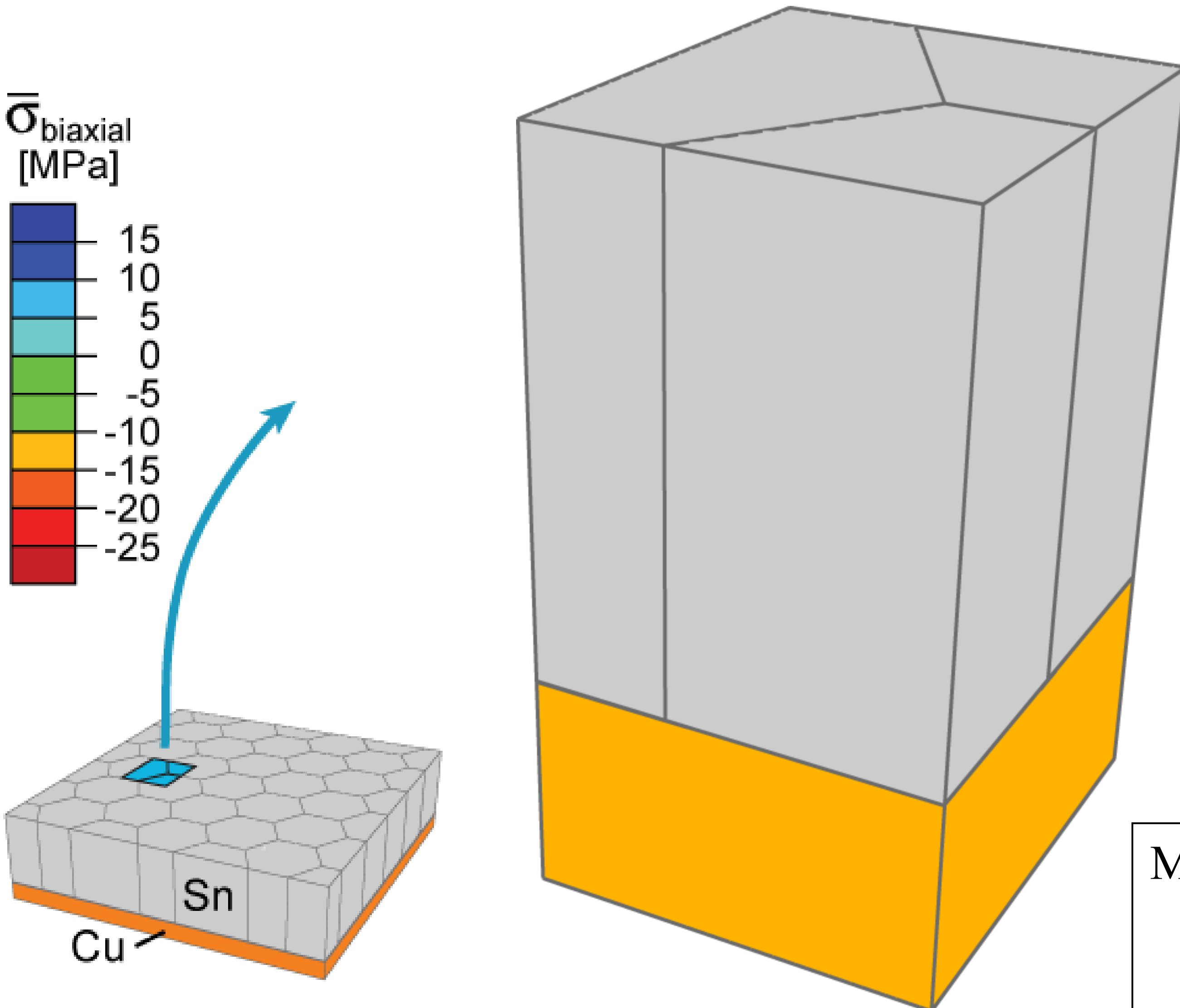


Grain-boundary diffusion elements



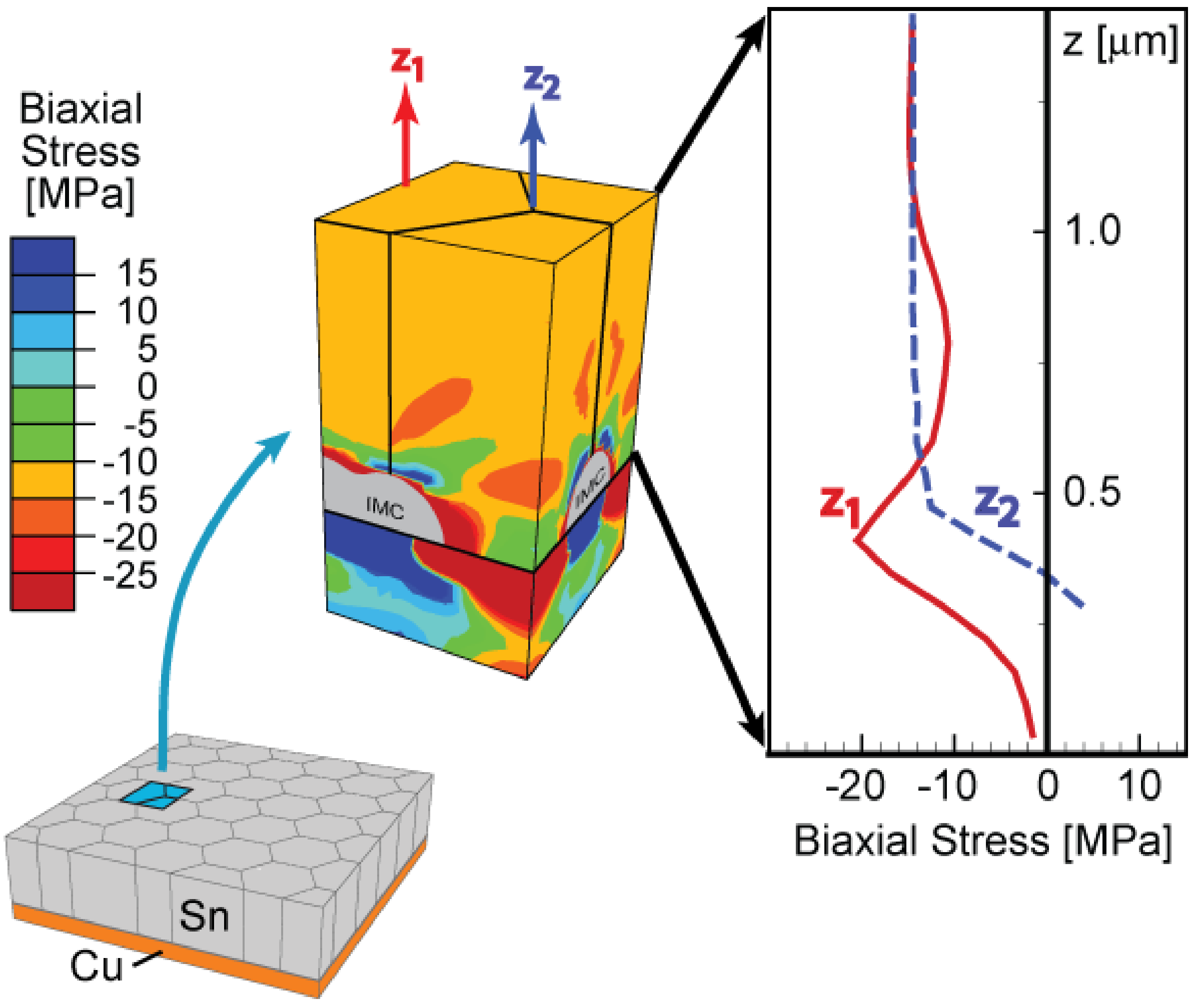
Calculate stress in Sn as IMC grows

(Buchovecky, JEM, 2009)



Mechanisms:
- -elasticity
- -plasticity
- - g.b. diffusion

Coupled grain boundary diffusion and plastic deformation transmit stress through Sn film

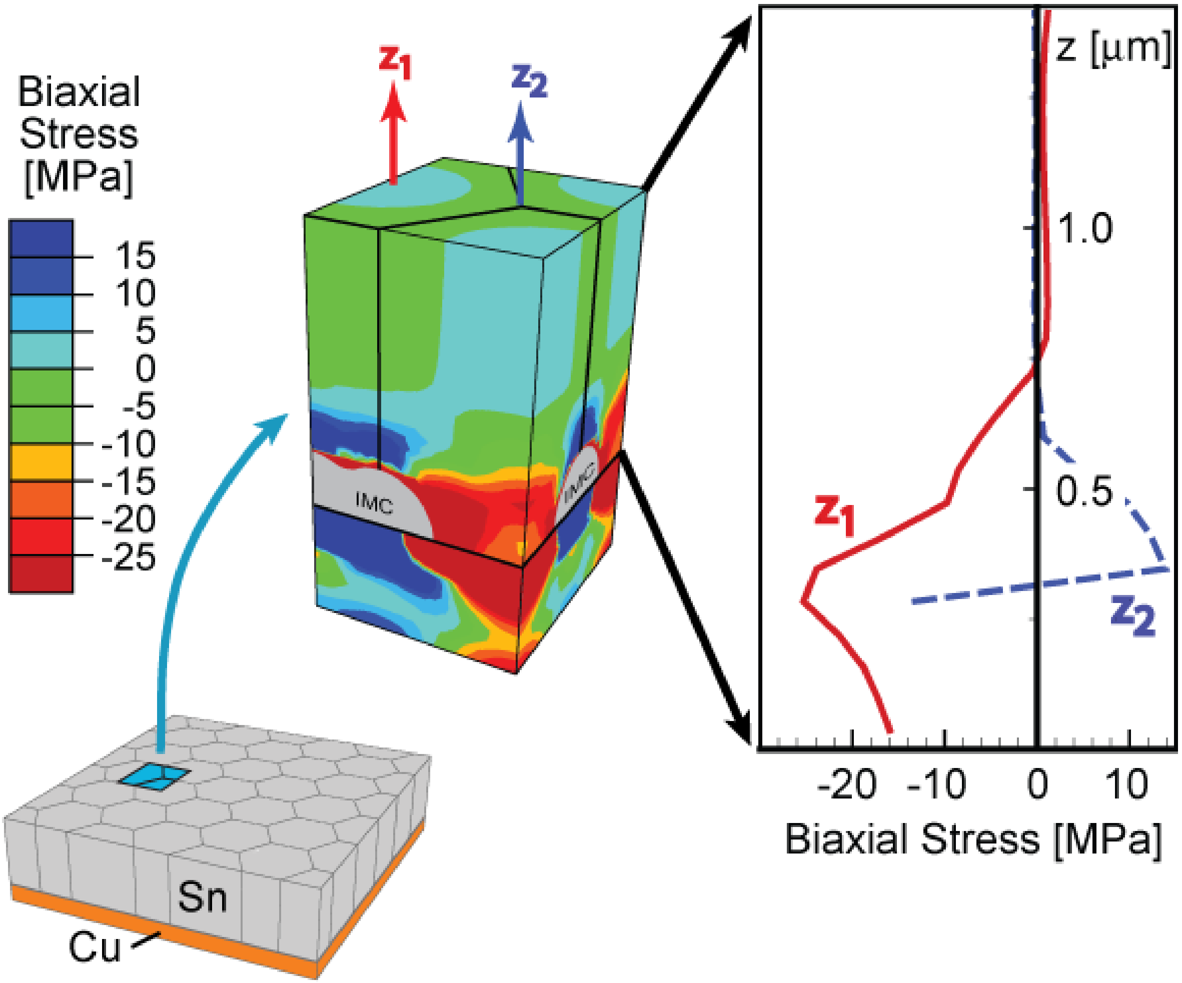


<u>With GB diffusion</u>:

- **IMC expands at Cu/Sn interface**
- **g.b. diffusion/plasticity makes compressive stress spread upward through the film.**
- **Stress through film is relatively uniform.**
- **Full thickness of film can reach yield stress.**

(Buchovecky, JEM, 2009)

Without GB diffusion, little stress is transmitted through Sn



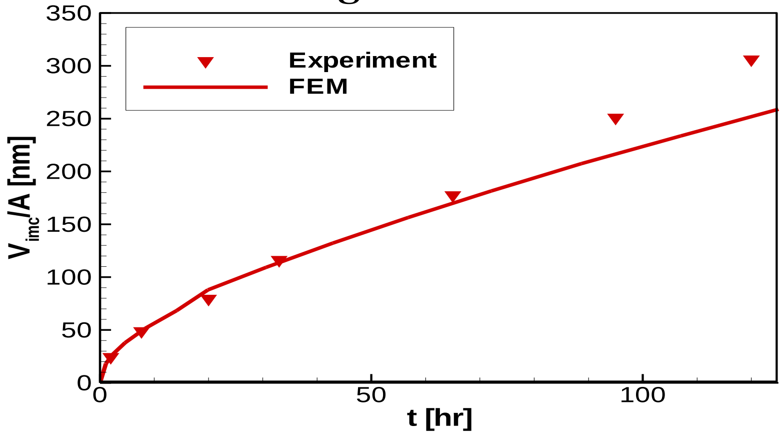
Without GB diffusion:

- **Compressive stress localized near IMC.**
- **Very low stress in much of the Sn, especially near surface.**

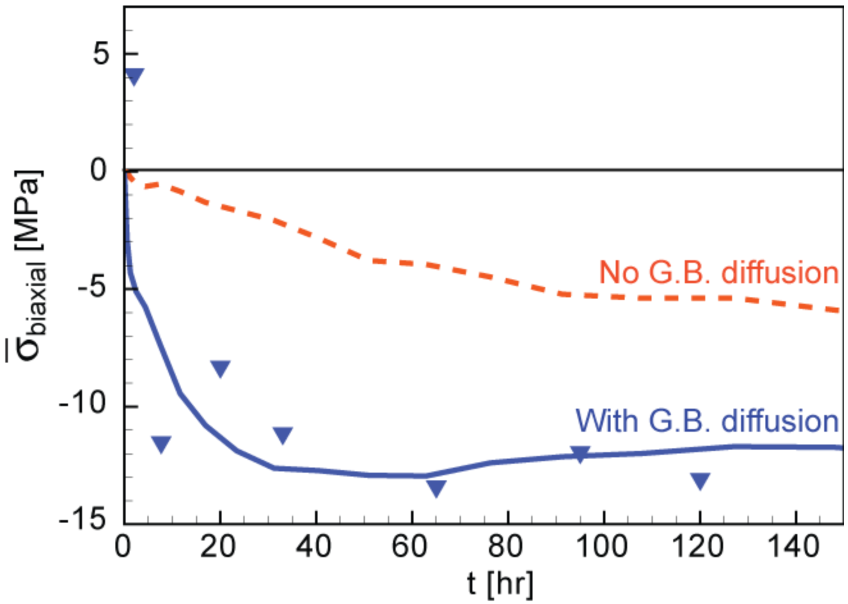
(Buchovecky, JEM, 2009)

Evolution of average stress with different relaxation mechanisms

IMC growth kinetics



Average stress in Sn from FEA



- Use IMC growth kinetics from experiments
- Calculate average stress over Sn thickness (as in curvature data)
  - *with g.b. diffusion*
  - *without g.b. diffusion*
- Elastic/plastic with g.b. diffusion similar to measurements
  - *Rapid rise then saturation*
  - *Stress spread across Sn layer*

FEA & measurements:
- **Stress spreads across Sn as IMC grows**
- **Due to plasticity and g.b. diffusion**
- **Saturates even w/o whiskers**

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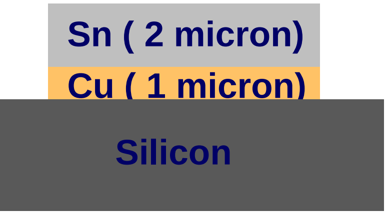
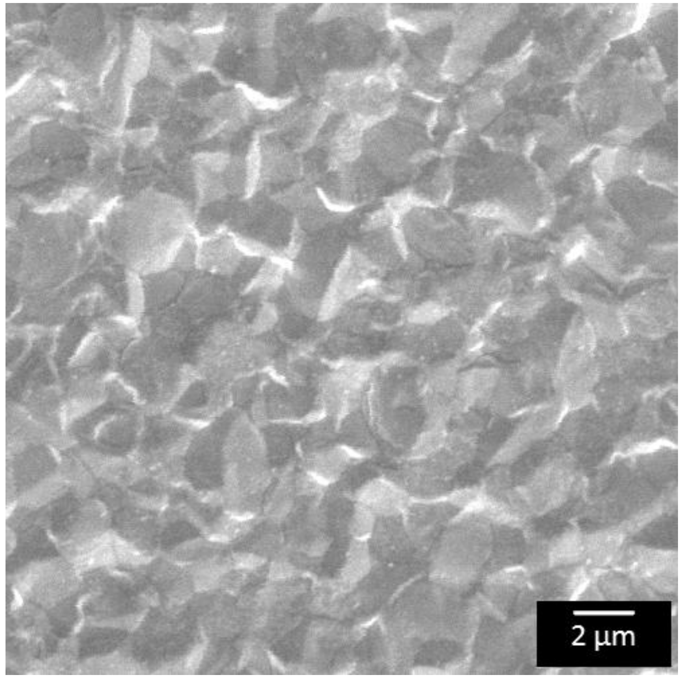
How do whiskers actually grow?



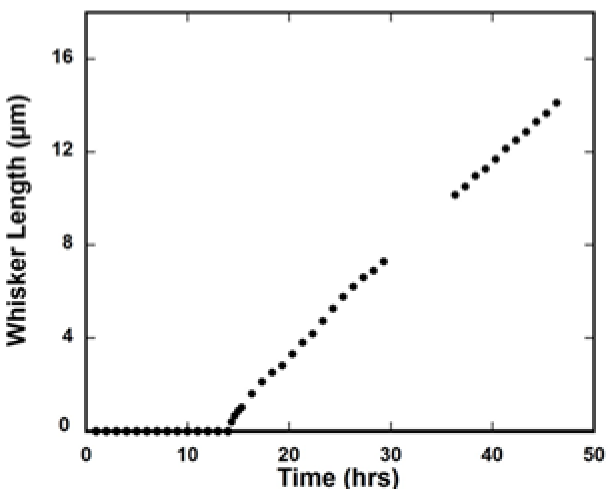
Movie #1

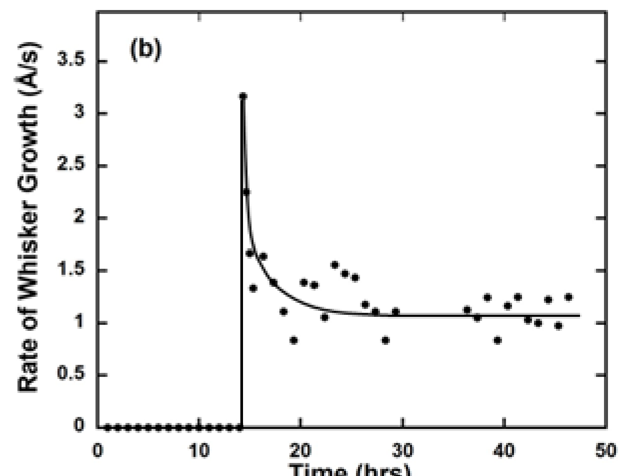


Real-time SEM/FIB

(see videos at: www.engin.brown.edu/Faculty/Chason/research/whisker.html)

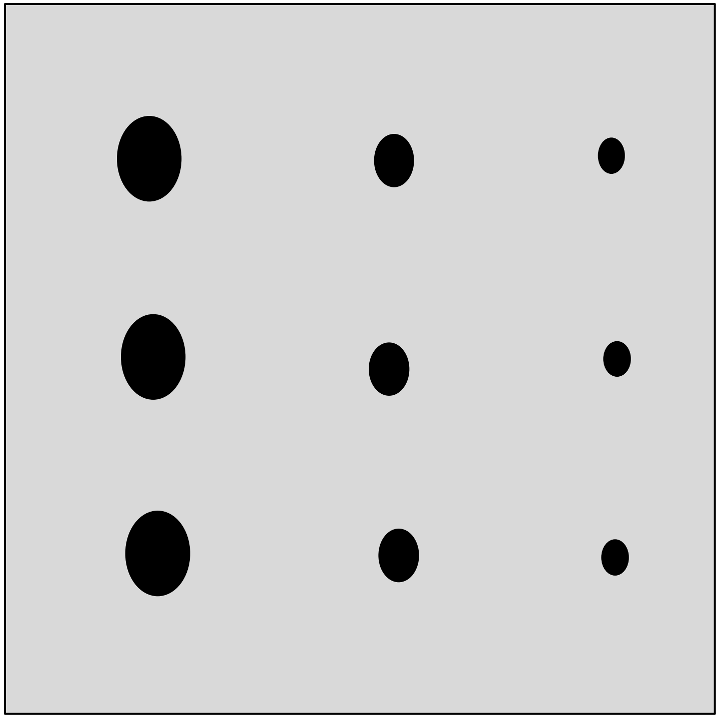
- **Incubation period of 12-13 hrs**
- **Whisker appears from single small grain**
- **Uniform growth rate in vacuum**
- **No prior surface defect before whisker nucleation**

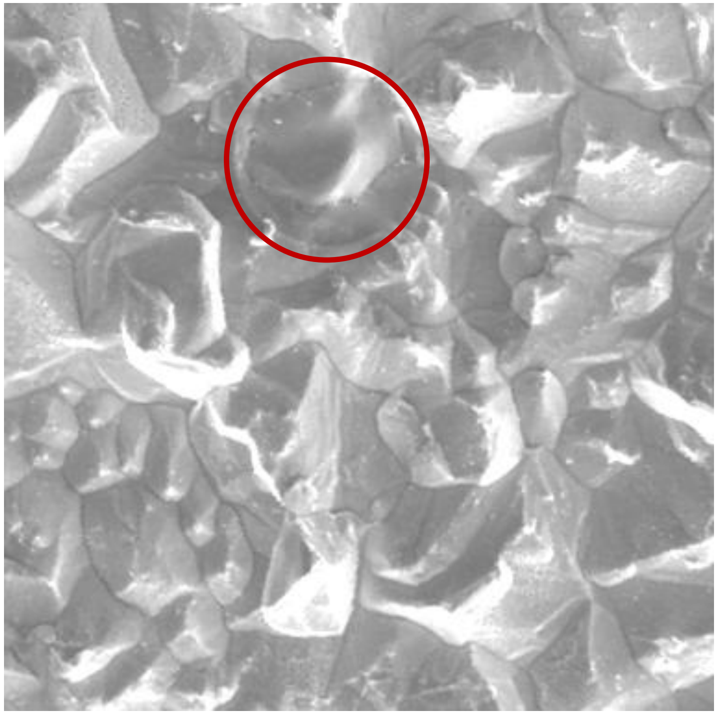




Nucleation not due to grains with weaker oxide layer

- Sputtered off oxide using FIB
  - 3 *3 array of holes of size .5,2 and 5 micron



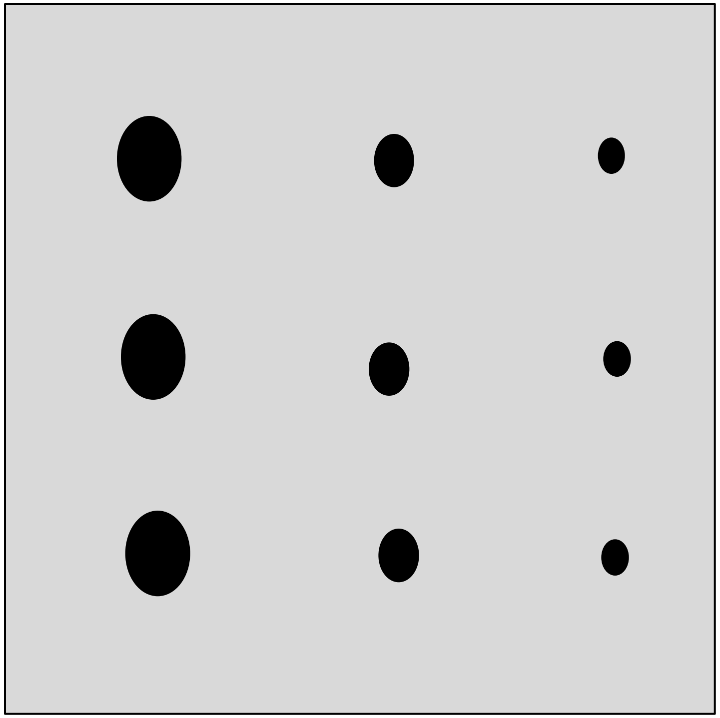


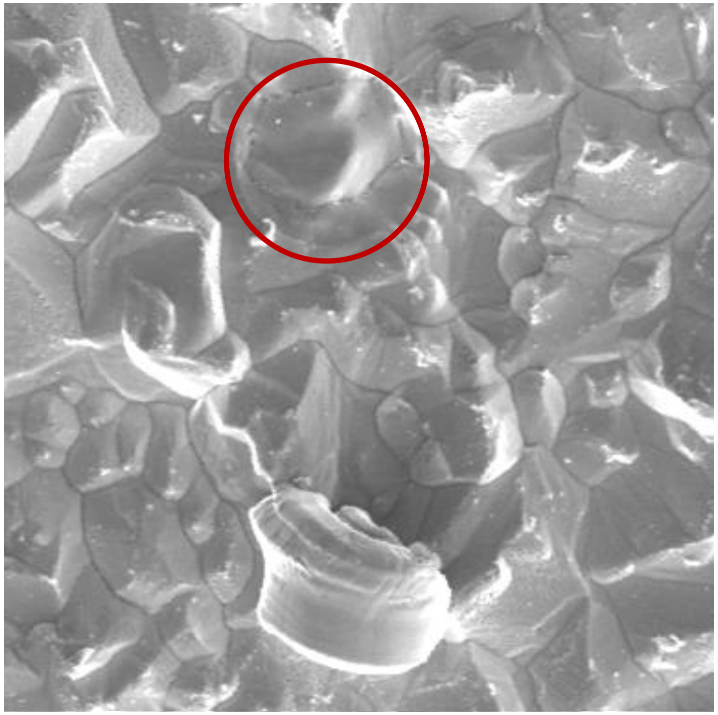
No whisker/hillocks nucleation from grains without oxide

- **Weak oxide is not sufficient to form whisker**

Nucleation not due to grains with weaker oxide layer

- Sputtered off oxide using FIB
  - 3 *3 array of holes of size .5,2 and 5 micron





No whisker/hillocks nucleation from grains without oxide

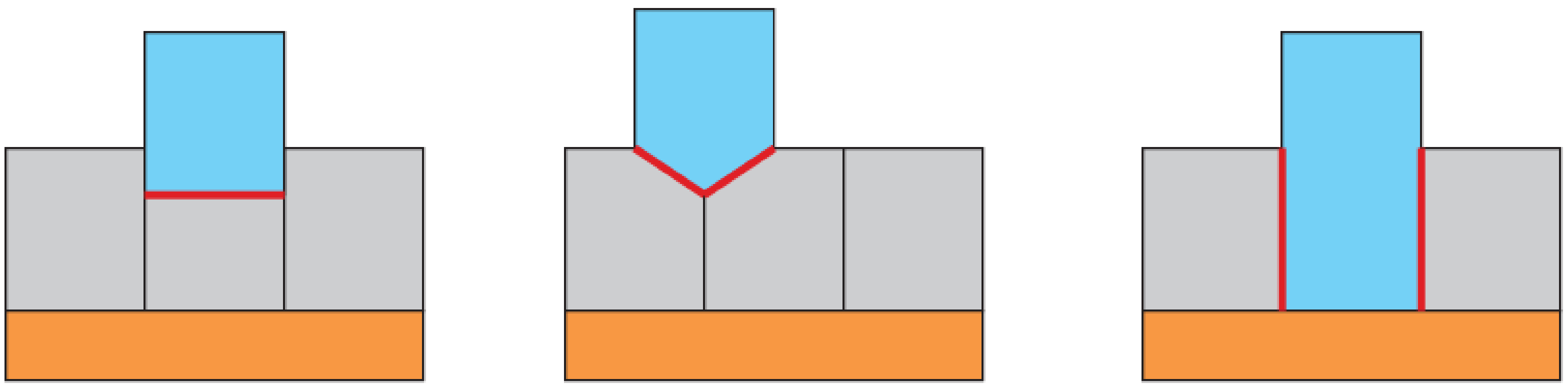
- **Weak oxide is not sufficient to form whisker**

Mechanism for whisker nucleation/growth

Enhanced stress relaxation at specific grains ("weak" grains)

Non-columnar grains
e.g., horizontal grain boundaries (Smetana)
Dynamic recrystallization

Plastically weak grain
Low yield stress



→ **Maintains low stress at boundary of weak grain**

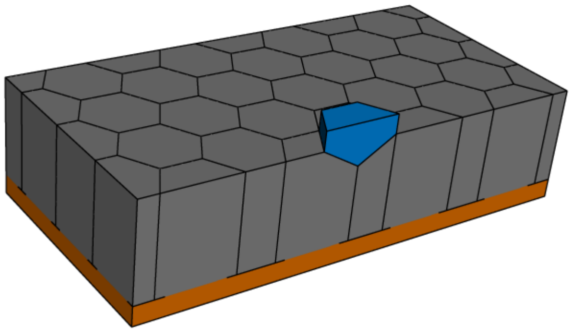
→ **Creates stress gradient**

- induces diffusion through g.b. network

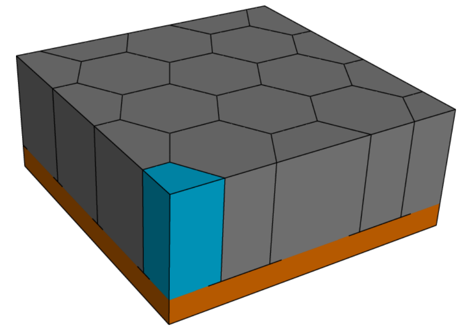
Add “weak” grain to FEA model to allow whisker growth

- Different mechanisms to maintain low stress at whisker:

Shallow whisker root with oblique grain boundaries.



Whisker with lower yield stress than other grains.



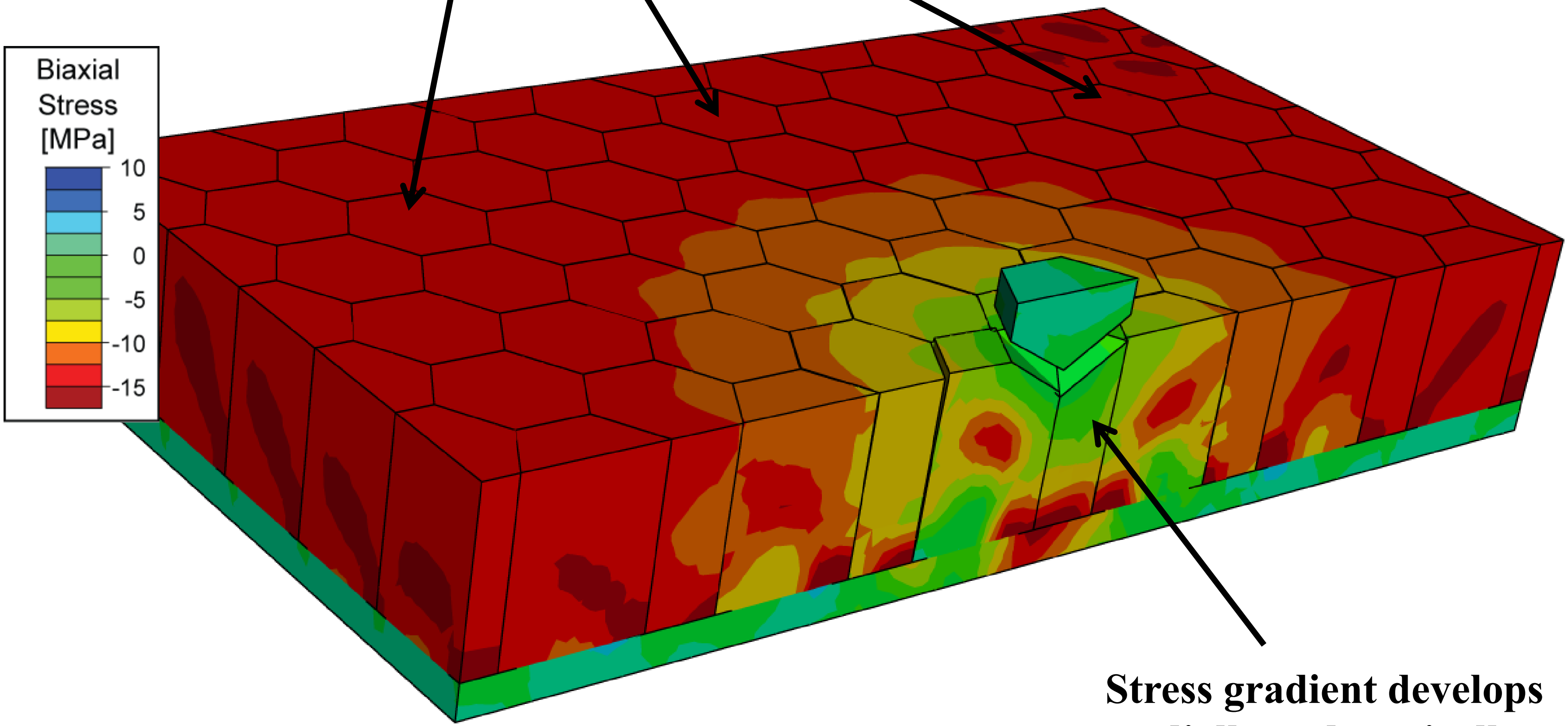
- Model IMC growth as uniform volume strain throughout Sn (IMC growth generates *excess* volume in Sn).

<u>Use FEA to calculate</u>:

- Stress field that develops around whisker grain.
- Rate of material transport to the whisker root (upper limit on whisker growth rate).
- Variables are IMC growth rate & whisker spacing.

Stress evolution with whisker growth

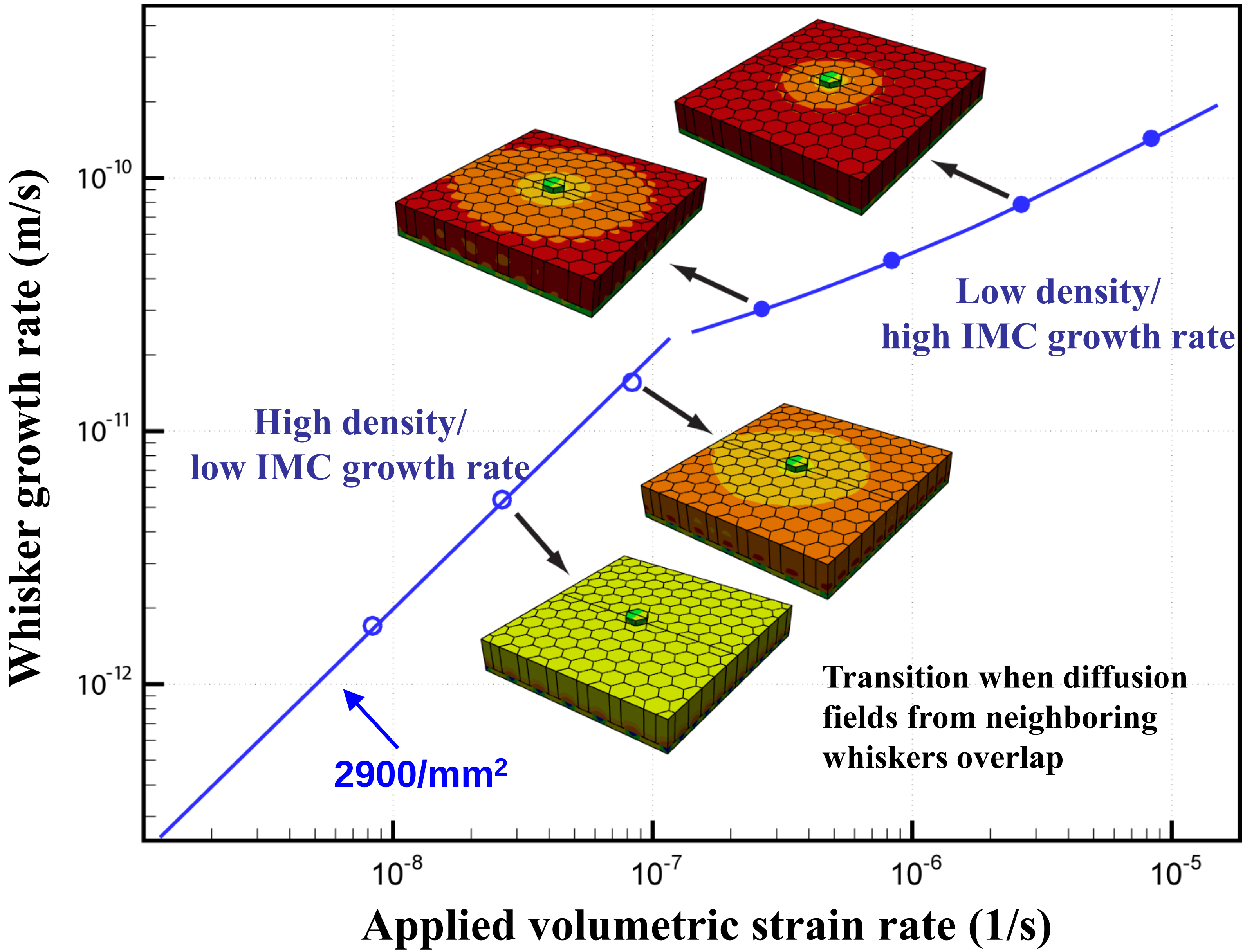
Large portion of film is at yield stress
(not relaxed by the whisker)



Stress gradient develops radially and vertically around the whisker root

(Buchovecky and Bower, APL, 2008)

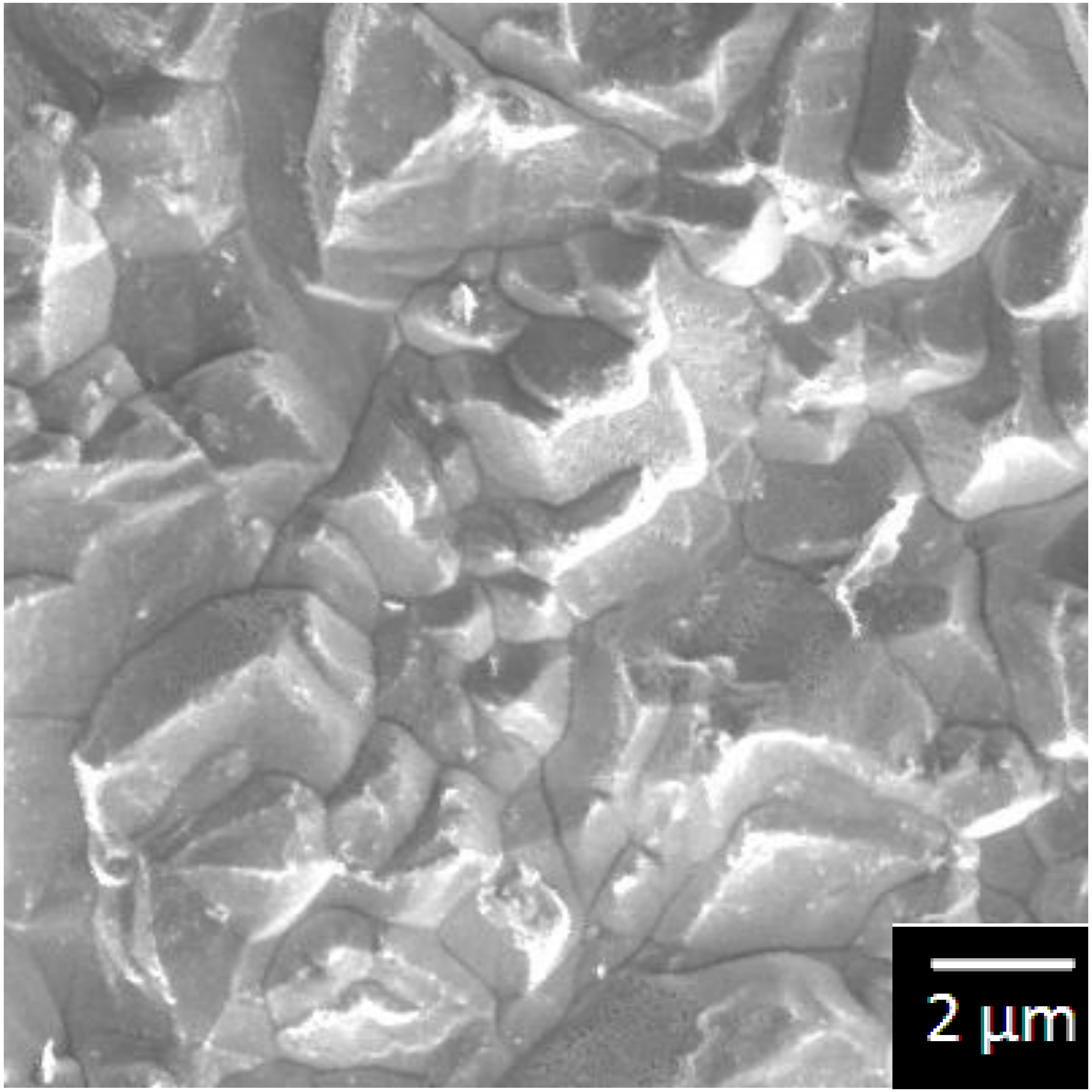
Whisker vs. IMC growth rate from FEA models



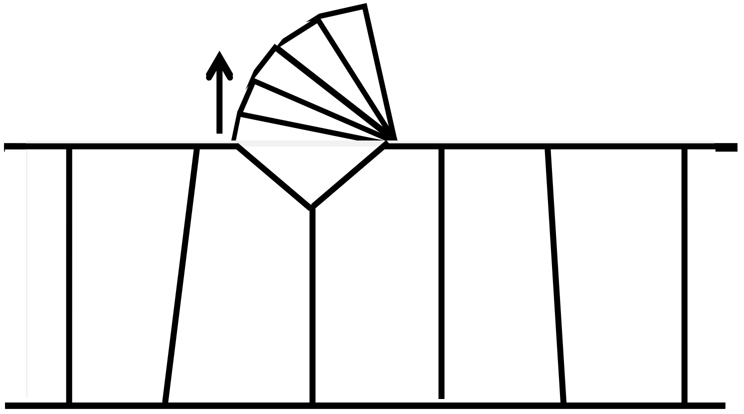
Other observations of surface evolution

Not only whiskers grow

Movie #5



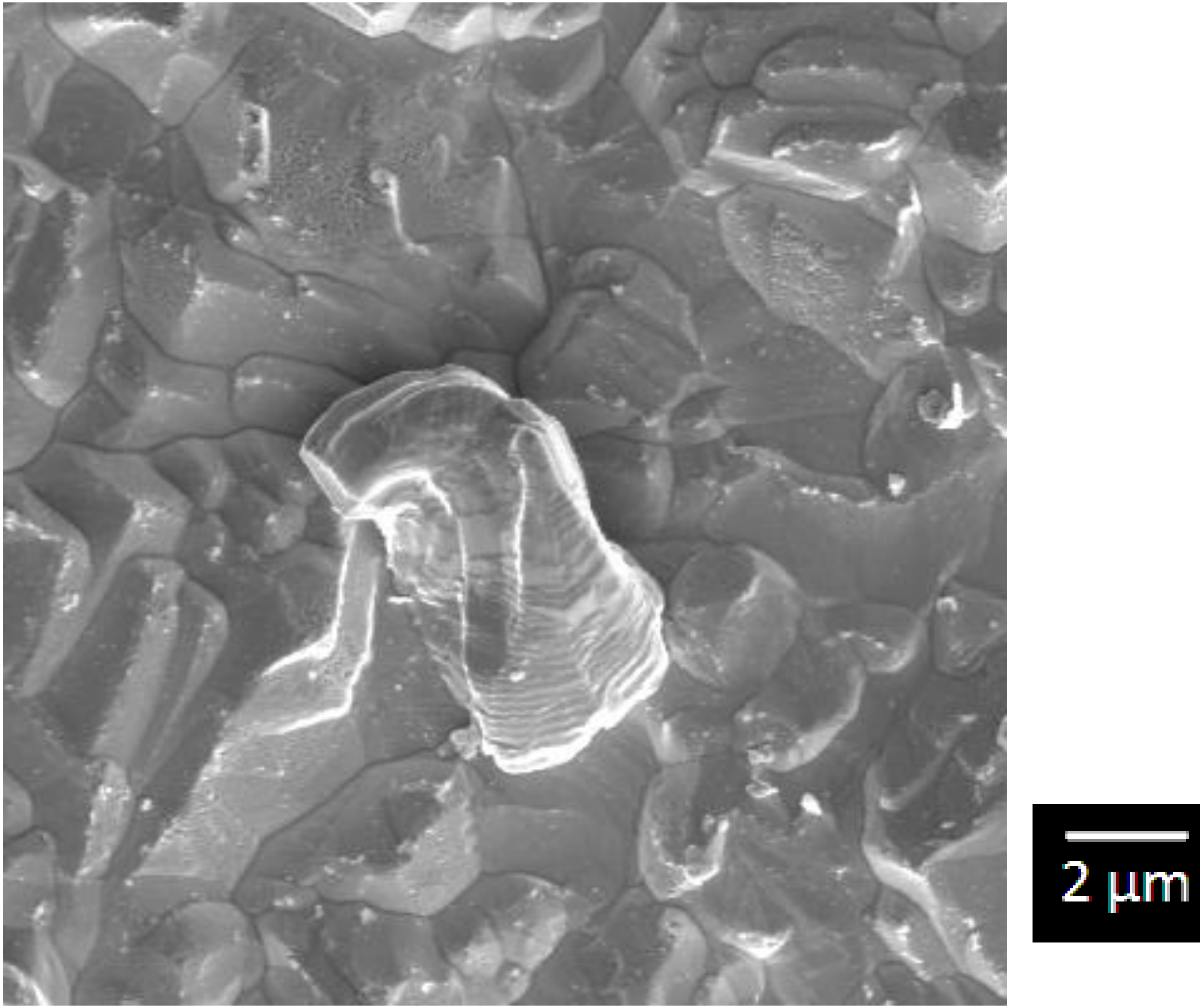
Schematic Explanation



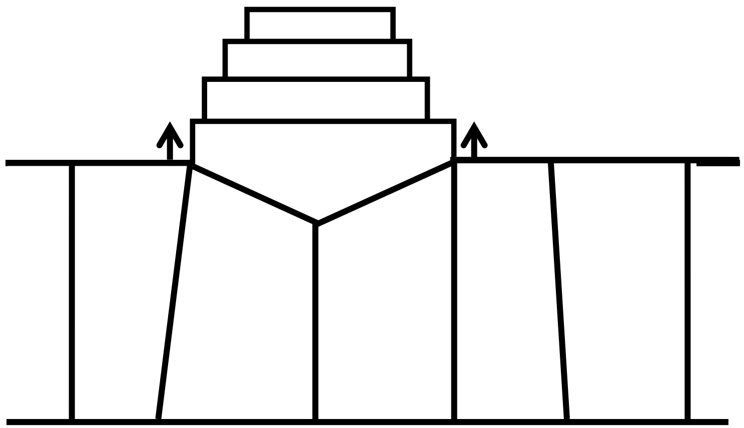
Tilt

What determine the hillocks shape ?

Movie #2

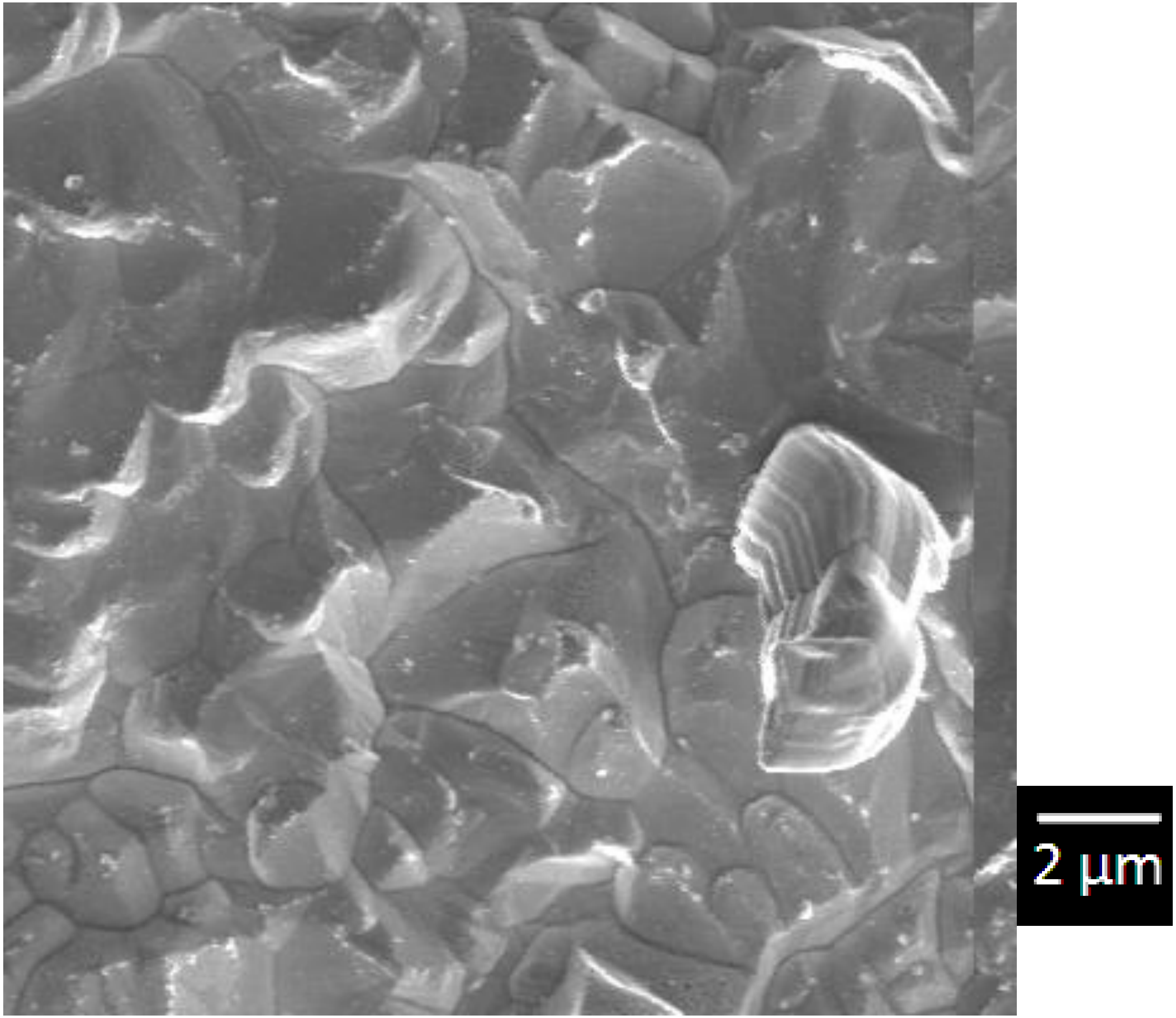


Schematic Explanation



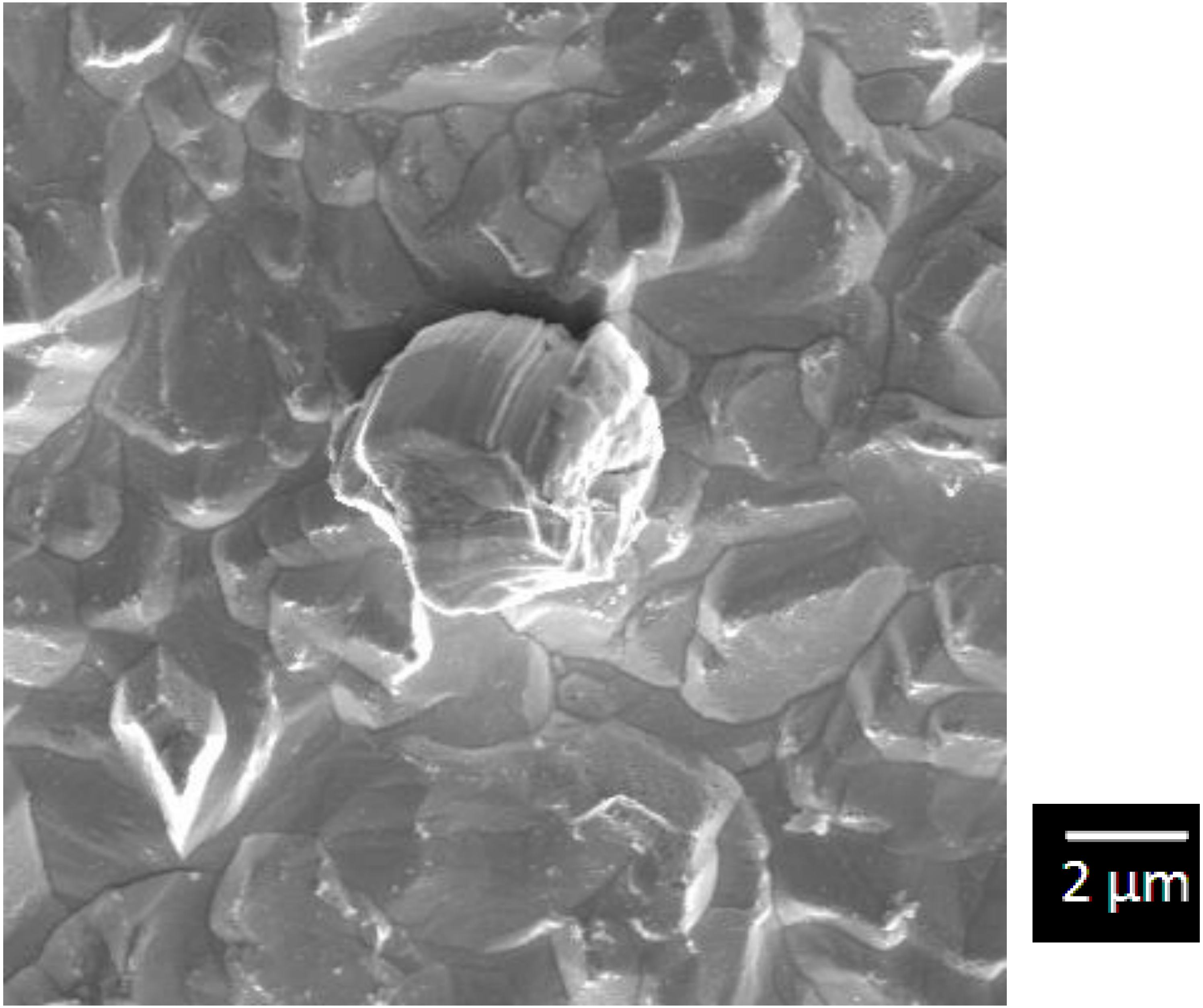
Hillocks nucleation and growth from partial grain

Movie #3

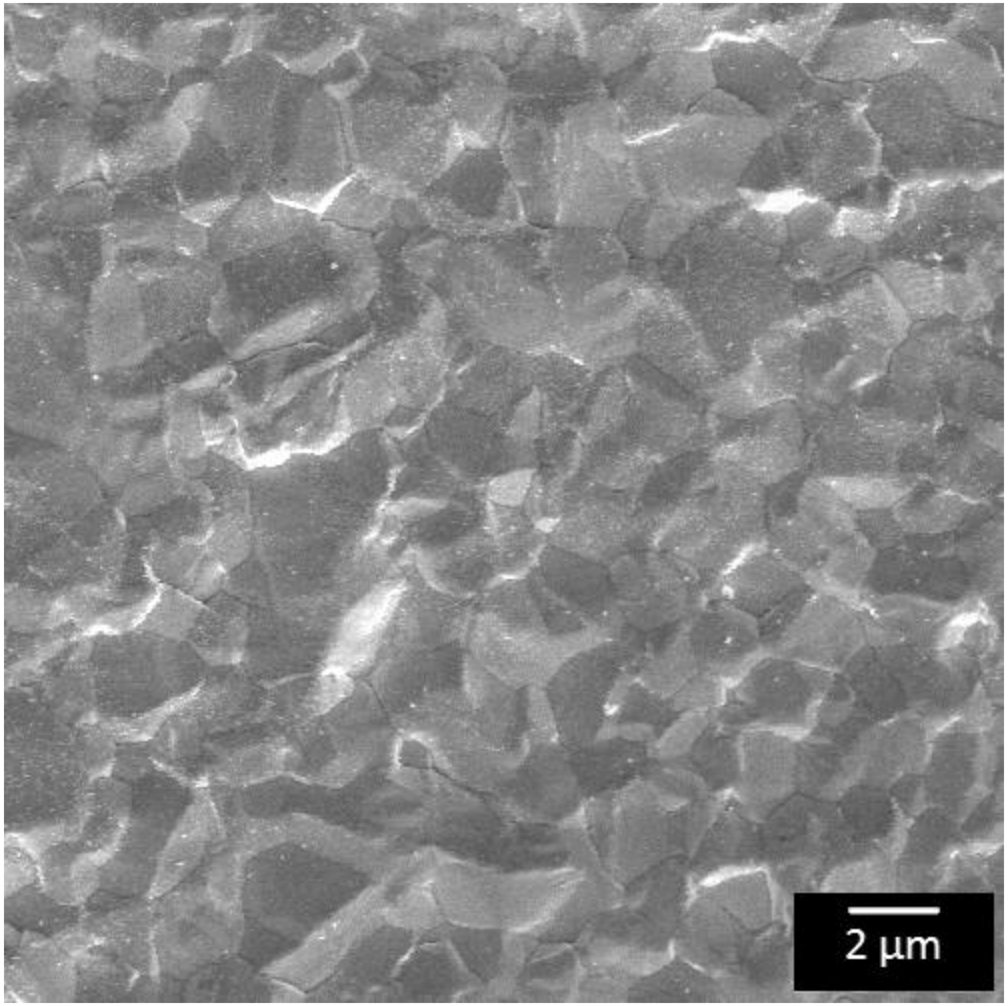


Grain growth then hillock pops out

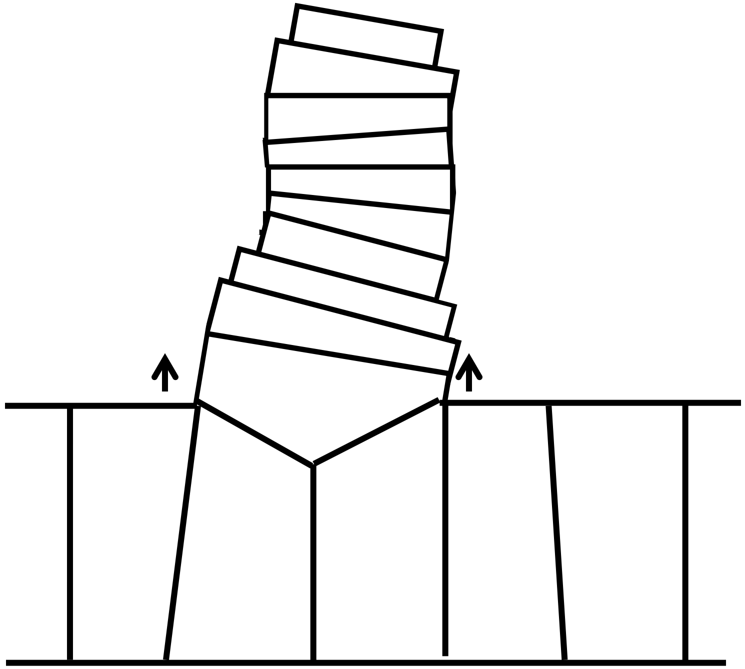
Movie #4



Grain Growth w/o hillock



Schematic Explanation



Complex morphologies

Combination of

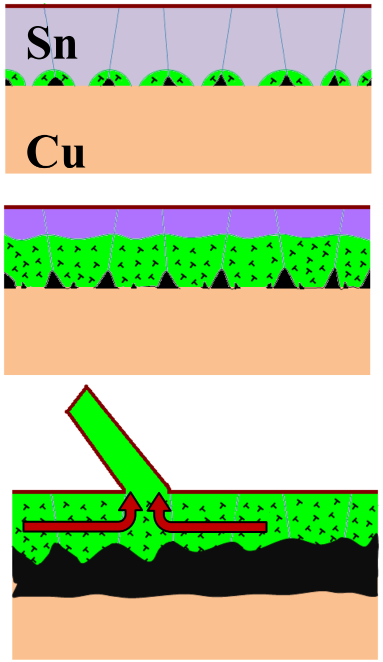
- **Vertical Growth**
- **Lateral (Grain) Growth**
- **Tilt**

Future

Model with FEA

- **Non-uniform stress**
- **Non-uniform mass flow**
- **Grain growth**

Summary - Mechanisms of whisker growth



1) Cu diffuses into Sn to form IMC
2) IMC grows → stress spreads through Sn
   - *dislocation motion/point defects*
3) Oxide prevents defect annihilation at surface
   – *stress builds up in layer*
4) Stress causes yield of "weak" grain
   – *allows whisker to grow*
5) Stress gradient drives diffusion to whisker base

Suggestions for mitigation

- Enhance stress relaxation in Sn
  - *don't strengthen Sn!*
- Modify microstructure of Sn or IMC to reduce stress
  - *promote horizontal GB's as sinks (like Pb)*
- Weaken oxide
  - *enhance stress relaxation at top surface*
- Diffusion barriers
  - *these don't stop driving force for whisker formation*

Thanks to my collaborators:

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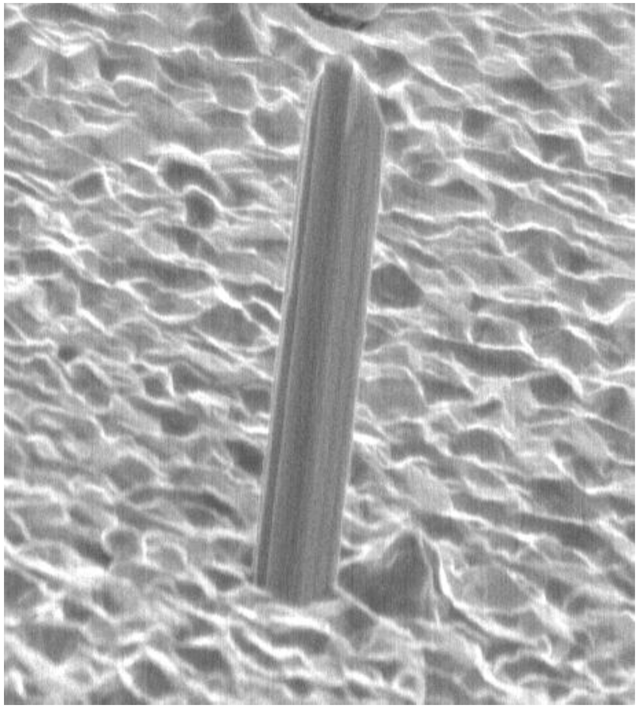
Lucine Reinbold (Raytheon)

EMC:

Gordon Barr



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